9.0 Nonlinear Optical and Electronic Materials

Electronic and optical technologies provide critical building blocks for all advanced weapon systems. They are required for information gathering, transmission, processing, storage and display, for the control of weapons systems, and for energy generation and direction concepts. Currently, the electronics and photonics industries are built on only a handful of materials, principally semiconductors, such as silicon and gallium arsenide, and a few solid-state inorganic compounds. We expect these materials to continue playing a major role in the industry. However, for higher performance systems, these materials are intrinsically limited, and new materials must be found and developed. In the future, a much wider array of materials, from novel multilayered semiconductors to new polymeric materials, will be available for advanced optical and electronic applications. These new materials will be designed and processed at the atomic scale to provide optimized electrical and optical properties to meet specific Air Force requirements. As our capability to custom design and grow new materials expands, electronics foundries will change to a flexible manufacturing format where the same growth and processing equipment will be used to create a wide variety of optical and electronic devices on demand.

These improved materials will make possible sensors with high sensitivity across the entire electromagnetic spectrum, data transmission links with greater than 200 gigabits/second, parallel processing of data at breathtaking speeds, three dimensional data storage with almost instantaneous access, and holographic cockpit displays. They will make possible the next generation of control systems such as the mounting of sensors and processors directly on aircraft engines. These materials will lead to new weapon concepts, such as directed energy weapons, as well as to the systems which counter them.

9.1 Electronic Materials

We categorize electronic materials as active or passive. Those considered in the following discussion have high potential for future payoff to the Air Force. In most cases evolutionary development is required to meet this potential. In some cases there are revolutionary possibilities as well.

Passive Materials

High Performance. Radome materials, which will ensure that the USAF can establish a position of air superiority and provide theater defense from missiles and high-performance hypersonic aircraft, must be developed by the DoD. This technology has little commercial use. Because of the extreme requirements on these materials, it will be necessary to establish and maintain a fundamental research base in materials development and processing in this area. A consistent, long-term commitment to develop high-temperature radome materials will provide materials of the future for hypersonic vehicles.

The radome is a critical component in numerous weapon delivery systems and often is the component limiting the performance of supersonic and hypersonic vehicles. There have been several surges in funding during the last few decades to develop suitable radome materials, but these efforts have often been abandoned due to the technical challenges of the problem, shifts in the political climate surrounding the systems, and the transfer of the technology responsibility from one DoD component to another. The area in which most of the progress has been made is in the development of millimeter-wave systems centered around 35 GHz. However, as weapon systems are miniaturized and the need for system resolution increases, the need for radomes operating at around 94 GHz will become significant. Additional target accuracy can be attained through the use of a multispectral targeting system. Such a system could employ both RF and optical tracking (IR or visible), along with ground/air-platform guidance.

The materials requirements on a hypersonic radome are extreme, with temperatures ramping up to 1000°C within a few seconds and the threat of high-speed rain erosion. In addition, the sensor system must be capable of seeing through the radome throughout the mission. This necessitates that the dielectric constant and attenuation (loss tangent) of the radome material to be relatively constant over a broad temperature range. Otherwise a radome must be designed that can be cooled. Previous efforts have met with some success in developing radome materials and concepts which meet the above requirements at 35 Ghz. The challenge is to move to shorter wavelengths. In all cases, materials processing has been a major stumbling block in successfully developing hypersonic radomes.

In the area of multispectral radome materials, polycrystalline CVD diamond appears to be a viable material for the future. In some respects diamond is the miracle material of the future, but there are some significant hurdles to overcome, especially when it comes to processing.

Advanced Tailored Dielectrics. Dielectrics often limit the achievable performance of electronic systems. A whole host of applications require the use of tailored dielectric materials, including permittivity (e) and permeability (m). Examples range from low-observable coatings to antenna systems. Regardless of the application, advances in materials technology are necessary to manufacture materials with tailored dielectric properties. Often the dielectric properties required are extreme and not achievable using current technology. For an example in the area of antenna miniaturization, an antenna element can be buried in high-dielectric-constant material, effectively reducing the physical size of the antenna while still allowing low-frequency operation. In some cases dielectric constants well over 1000 are desired without any associated loss due to absorption. One approach to achieving this type of dielectric behavior is to use dielectric mixtures. The processing of such materials is often difficult and not easily repeated. In addition, current tailored dielectrics are often not very robust. Future supersonic platforms will require advanced tailored dielectric materials capable of withstanding the rigors of supersonic flight without a loss or change in the dielectric properties of the materials.

Organic Conductors. Electrically conductive polymers first aroused interest about 20 years ago. The major materials explored to date are polyacetylene, polypyrrole, polyaniline, and polythiophene, although many others have been reported. In spite of all the investment in polyacetylene, it remains an intractable and environmentally unstable material. It will not likely see any technological uses. Polypyrrole is commercially available, but is not a well defined material. More importantly, it is not processable and suffers from long term stability problems. It has, however, been incorporated into some electromagnetic interference (EMI) shielding applications. Polyaniline is being commercialized by the civilian sector, but suffers from moisture instability and often the conductivity levels vary by orders of magnitude depending upon the moisture content. These characteristics, and its inability to withstand harsh environments, make it unsuitable for pressing Air Force needs. Polythiophene is still a laboratory material, but it warrants serious consideration.

The applications of conductive polymers are myriad. Light-emitting diodes, photovoltaics, and corrosion inhibition based on conductive polymers have all been demonstrated. The Air Force has interests in all of these areas and should nurture their R&D. It especially needs conducting polymers as engineering materials for gap sealants, conductive matrix resins, and conductive wires. These are niche applications that are not likely to be addressed by non-DoD efforts. Industrial efforts are unlikely to address these critical needs. Air Force leadership in discovering and developing new, environmentally and thermally stable conductive polymers is needed.

Magnetic Materials. There are opportunities for impressive advances in airborne power applications for more-electric-system-concepts that depend on advances in magnetic materials. These include both near term and far term work on improving soft and hard magnetic materials for AF specific high strength/high temperature/low electrical loss applications, of which starter/generators and magnetic bearings are a subset. In the long term, there are real possibilities for nano-structure or meso-structure technologies to provide superior advanced magnetic materials. Laminated solids could replace the present physical stack of laminations, separated by a thin insulator, as core materials for generators and motors. Near term, diffusion-bonding techniques for metal-to-metal and ceramic-to-ceramic interfaces would improve the stiffness and strength of core materials.

Impressive evolutionary improvements seem possible. Examples are twice the mechanical strength and an order of magnitude lower electrical loss, 550°C operating temperatures for soft magnetic materials, and an increase in operating temperature for hard magnetic materials from 300°C to 450°C, with extended life at these temperatures and a factor of two increase in energy density. This is possible by optimizing known systems, the 50 percent Fe - 50 percent Co class of soft materials, and improving hard rare-earth/cobalt magnets of the 2:17 type of the form,

$$Sm_{(1-u-v)}LRE_{u}HRE_{v}(Co_{1-w-x-y}Fe_{w}Cu_{x}Zr_{y})_{z}$$

where LRE and HRE are light and heavy rare earths respectively, and the overall ratio of rare earth to the other metals is 2:17.

Breakthrough capabilities should also be pursued, since they can lead to even greater performance gains. For example, each enhancement factor of 3, 5, 10 or 15 in magnetic properties over the two baseline systems would be important as performance increases with the square of the attainable magnetic induction field. Raising the Curie temperature to 2000°C or 3000°C would be a boon to many new high-payoff applications.

Active Materials

Multilayered Semiconductors. In recent years major steps have been made toward a new approach—bandgap engineering—for designing and growing semiconductor structures with tailored electronic and optical properties. By controlling the composition and thickness of multiple semiconductor layers, the electronic band structure of this multilayered material can be tailored to achieve desired properties in a nearly continuous way. The development of highly controllable deposition systems for semiconductor thin films, such as molecular beam epitaxy

(MBE) and metalorganic chemical vapor deposition (CVD), has made it possible to grow ultrathin (10 - 100Å) epitaxial layers of various compositions on semiconductor substrates on an atomic layer-by-layer basis. Thus, the opportunity now exists to custom-design semiconductor structures with unique electronic and optical properties that are unattainable in single-layer materials.

So far, only a few of the many possible semiconductor alloys have been grown in multilayered structures. But even these few alloy combinations have provided many new electronic and optical capabilities such as solid-state lasers, high electron mobility transistors (HEMT) and quantum-well infrared photodetectors. The next advances will be to establish the specific epitaxial growth processes and conditions for new alloy compositions and layer combinations, and to move beyond multilayered structures with the same lattice constant as the growth substrate. These advances will greatly widen the array of materials choices available to future "bandgap engineers." For instance, patterned substrates would enhance the capability to grow high-quality lattice-mismatched or strained semiconductor layers. In addition to current planar epitaxial layers, growth techniques for controllably growing quantum wires and dots of semiconductor materials need to be developed. To take full advantage of bandgap engineering, quantum mechanical models for predicting the electronic and optical properties of new multidimensional structures are required, as well as growth-process modeling of epitaxial deposition systems. Some such models are already under development, but need to be broadened to cover many materials and designs within the same simulation, instead of the current practice of modeling one specific material or design. These models will greatly reduce the time it takes to develop an advanced electronic material for a given application.

In addition, development of new growth and production processes for present III-V based semiconductors, such as direct-write selective area epitaxy, will enable multifunctional devices on a single electronic chip. The integration of several electronic and optical functions into the same chip will provide faster devices, miniaturized systems, and more reliable systems. A great many electronic failures in military systems are due to the thermal environmental effects on the wire bonds used for connecting devices. New ways of producing devices which reduce the number of wire bonds will significantly improve reliability and lifetimes. Direct-write selective area epitaxy, a process for growing different semiconductor device structures on the same substrate, is one technique envisioned for bringing about multifunctionality. The use of textured substrates is another method which could provide the capability of growing more than one type of semiconductor heterostructure on the same substrate, possibly at the same time. These technologies would revolutionize the way electronic chips are fabricated by eliminating the need for lithography, thereby greatly reducing the number of device processing steps and their associated costs.

As an example of how the development of multilayered semiconductor structures could impact future Air Force capabilities, we consider infrared detector imaging arrays. Multilayered semiconductors would allow multispectral imaging using one focal plane array instead of separate arrays for each wavelength band. Multispectral imaging allows better discrimination between the background and target, providing the warfighter with a sharper image. Besides integration of multiple wavelength bands in one detector, first-level signal processing for this sensor could be integrated onto the same chip. By performing first-level integration on the same chip as the detector, the sensor becomes smarter and a layer of complexity is removed from the device processing. These capabilities would provide the advantages of smaller, more compact sensors that are lighter, use less power and provide more information.

High-Temperature Wide-Bandgap Semiconductors. Silicon carbide (SiC) and the other wide-bandgap materials will be instrumental in developing device technologies for the next 30 to 50 years. These materials offer the potential for an enormous range of applications, many considered impossible for conventional semiconductors. Some applications where SiC-based devices will be applied include electronics for hostile environments—high temperature electromagnetic radiation, high-power solid-state uncooled radar, and high-power switching and blue laser-based communications systems. In addition, wide-bandgap semiconductors capable of emitting and receiving signals in the blue and ultraviolet portion of the electromagnetic spectrum will receive increasing attention for optical computing applications, where these short wavelengths will provide much wider information bandwidths. Defense requirements for high-temperature, high-power-density electronics include power components, engine sensors, distributed processing for the More-Electric Aircraft (MEA) initiative, and uncooled microwave components for radar and communications. To meet these requirements, and increase reliability and affordability, breakthroughs in materials processing will be required.

SiC single-crystal material of adequate quality and size for demonstrating general electronic applications has only become available within the last few years. Wafers are available which are small and loaded with defects and impurities when compared to silicon. Only the simplest devices have been demonstrated, and these were made small in area to avoid defects such as pinholes in the wafer. However, these devices have demonstrated the technical feasibility and tremendous potential for future applications. A lot of material and process development will precede the insertion of SiC-based electronics on critical aircraft systems. Routine use for these devices in electric vehicles, MEA, communications and power management systems can be expected within 20 years.

Thin-Film High-Temperature Superconductors. With the discovery of the superconducting copper oxide compounds (called the high-temperature superconductors), superconductivity is poised to make a greater impact on technology and society in the next century. Whether or not superconductors can have the same dramatic impact of semiconductors depends a great deal on further improvements in these materials. As the processing techniques for thin films continue to improve, it is anticipated that some of these materials will work their way into microwave communication systems, acting as filters and antennas. RF circuits made using superconducting thin films provide orders of magnitude performance improvements while also reducing size and weight. The Air Force is currently developing high-temperature superconductor switchable filterbanks which will provide new capabilities for aircraft to filter out extraneous radar signals that could confuse onboard radar warning receivers in the modern-day electronic warfare environment.

While some applications are nearing the demonstration phase, other applications for high-temperature superconductors are 20 years or more in the future. A technology for making reliable Josephson junction circuits needs to be developed for signal processing applications. Josephson junctions, fabricated by sandwiching a thin normal metal or insulating barrier between two superconducting layers, can be made to turn on and off rapidly with low power.

These junctions could replace the circuits now used in computers and significantly reduce the power used and theoretically increase the speed of computation by up to 50 times.

Development of high-temperature superconductor technology is also required to manufacture practical superconducting interference devices (SQUID) capable of detecting extremely small variations in magnetic fields too small to be sensed by conventional means. SQUIDs could be used to detect very small deep cracks and hidden, inaccessible corrosion in aircraft structures. The Air Force should play a leading role in developing this technology because of the importance of nondestructive evaluation/inspection (NDE/I) for aging aircraft. As one example, it is envisioned that hand-held scanners based upon high-temperature superconductor technology could be developed to reliably detect corrosion hidden inside wings, a significant problem for aging aircraft in the Air Force.

Finally, even greater technological change may result from basic research on superconductivity. Once the materials and mechanisms are understood, even higher transition temperatures may be reached. Even if room-temperature superconductivity is not possible, raising the transition temperature to temperatures attainable with technology used in household air conditioning is not an unreasonable goal. Additionally, molecular-based superconductors which are currently laboratory curiosities should be considered. Very little is understood about how to build such materials. This is a fertile area for increased, broad-based research, spanning theory, modeling and synthesis.

9.2 Optical Materials

Optical technology is the science of employing light (i.e., photons) to perform various functions. It has been responsible for many recent technological breakthroughs, such as the IR imaging technology demonstrated during Desert Storm and the fiber-optic communication system which now links our world. However, we now appear to be in a historically significant period of R&D for optics, from which a revolutionary optical technology with greatly expanded capability has begun to emerge. This technology is nonlinear optics, which includes *electro-optics* and *photonics*. It provides active building blocks to the system designer's armamentarium in the same manner that semiconductor devices provided the building blocks for the electronic revolution. Continued evolutionary improvements in linear optical materials are needed as well as revolutionary changes in nonlinear optical materials.

Linear Optical Materials

Multi-Spectral Windows and Domes. With the increasing reliance on optical sensors to perform numerous Air Force missions, it is becoming necessary to acquire imagery through several spectral windows. The common atmospheric transmission windows are the visible, near-infrared, mid-infrared, far-infrared and mm-wave. Each spectral window has its own benefits and shortcomings. For example, visible scenes offer the greatest resolution, but a visual scene can be easily obscured by darkness or bad weather. Thermal imaging can pierce the veil of darkness but has limited success in bad weather. Millimeter-wave imaging offers all-weather operation, but does not offer high resolution images. The availability of multiple imaging sensor systems provides the ability to operate under all conditions and provides additional dimensions for target identification.

It is expected that future electromagnetic countermeasures will extend throughout the usable spectrum, and multiple spectral windows will provide an element of redundancy necessary to increase the probability a weapon system can complete the mission.

It is advantageous for several reasons to combine several sensors into a single suite which looks through a single aperture. Unfortunately, there are only a few materials currently available for use across the spectrum, and all these materials have poor physical properties with regard to durability. New multispectral optical materials capable of operating under harsh environments are required. Diamond suits the needs for many of these applications, however it will have limited applicability in the mid-infrared. High quality, ultralow-loss remains a significant materials challenge. For this reason the Air Force must continue supporting the development of diamond coatings, windows and domes and must as well investigate the potential for new multispectral window materials.

Advanced Coatings. Optical coatings are used in every optical system deployed. As these systems become more complex, the demands on coating performance increase. Many coatings must withstand harsh conditions, such as dust and rain erosion as well as provide a high degree of optical performance over multiple spectral bands.

Specialized optical coatings must also provide protection of optical sensors against specific optical wavelengths employed as laser range-finders and designators. Several technologies have been developed to meet the demanding spectral characteristics, but in some applications their cost is prohibitive or performance is marginal. Future technologies, including structured polymer films and spray coatings offer the potential to enhance the performance in selective areas while reducing the cost of deployment.

High-Performance Dyes. The necessity to protect a pilot's eyes from laser range-finders and designators requires the use of laser eye protection incorporated into the helmet visor. The performance of available dye-based visors is far from ideal. The spectral requirements on dyes employed for vision protection are many and demanding. In addition to the spectral requirements, these dyes must exhibit environmental stability and be compatible with an appropriate fabrication process.

During the last decade, great strides have been made in the fundamental understanding and in the ability to calculate photochemical processes at the molecular level. With this new understanding as a backdrop, the potential exists for considerable improvements in the performance of laser protection dyes. The development of new, high-performance dyes will require the use of computational chemistry approaches coupled with an intensive synthetic program. The design of future high-performance dyes will be based on a solid understanding of the electronic structure of the materials and their interaction with various host materials.

Holographic Materials. Optical holography is a technique based on the interference of two optical beams to write intensity and phase information into a solid material. Holography applications range from spectral filtering to information storage. For example, holography is one technology employed for heads-up displays (HUD) in fighter cockpits. In the future, holography has the potential to impact a much wider range of applications, including ultrahigh-bandwidth communication systems, ultrahigh-speed and density data access for complex computational tasks (e.g. target recognition), and laser eye protection.

Existing static holographic recording materials are typically based on photochemistry and use the photographic process. Unfortunately, these materials are temperature and humidity sensitive, cannot be made very thick, and are quite costly to produce. All of these characteristics limit the applications which holography could make and impact. The future will require new materials which are more robust, offer higher information storage density, and are inexpensive to produce. One potential class of materials which may meet these requirements is photosensitive silica-based glasses. These relatives of glass-ceramics are demonstrably capable of very high density information storage, however, little is known about the thermodynamics and kinetics of these materials. Research on this class of materials is necessary for it to eventually meet the demanding requirements of future holographic applications.

Polymer dispersed liquid crystal (PDLC) is another class of holographic material under current study. It can function as a two-state hologram. This class of material can be switched from “clear” (that is, no hologram visible) to “on” (hologram visible) by applying an electric field across the thick film. Although early in the development, these materials offer the potential of switching holographic optical components (e.g. lenses and filters) for use in optical devices, as well as optical correlation systems (e.g. target recognition). Considerable research and development is still required for these materials to realize their potential, especially in the area of materials processing based on the thermodynamic phase stability and kinetics of these multicomponent polymer systems.

Integrated Optics. It is likely that the capability of photonic circuits will exponentially increase just as electronic circuits have over the last three decades. It is not unthinkable that photonics will pass through a similar process of miniaturization and increasing complexity over the next several decades. Optical materials technologies will be key in the development of photonic industries. One materials technology which will likely undergo an evolutionary development is that of integrated optics. In the same way that enhanced lithographic processes have made electronic integrated circuits increasingly more powerful, new processes to write precision optical pathways must be developed in order to realize the photonics revolution. Several technologies currently exist to generate optical pathways in integrated optical devices. They are relatively crude, and there is a lot of room for these technologies to be developed.

Other technologies may also play a significant role in the future of integrated optical components, such as holographic interconnects. Holography offers the potential of opening up the third dimension and opening up the possibility for ultradense photonic circuits. It is difficult to predict where this technology will lead. The promise of optical processing at immense bandwidths dictates the need for research in this technical area.

Nonlinear Optical Materials

The advantages of nonlinear optics (NLO) over electronics for information manipulation include immunity from electromagnetic interference, elimination of electrical short circuits and ground loops, safety in combustible environments, low-loss transmission, large bandwidth, security from tapping, possibility of 3-D integration of devices, small size and light weight, and inherent paralleled processing of data for orders of magnitude increase in computing power. In addition, NLO can significantly improve the performance and character of laser sources providing new capabilities such as 1) wavelength conversion offering new discrete wavelength lines and wavelength tunability over a much broader spectral range than is possible with chemical lasers, 2) amplification, 3) Q-switches for pulsed lasers, and 4) optical phase conjugation for more ideal beam profiles and the coupling of laser beams. On the distant horizon, all optical data processing promises orders of magnitude increases in computing power.

Nonlinear optical responses are divided into second-order and third-order effects. In simple terms, a second-order material can be used for generating new laser wavelengths, for the photorefractive effect yielding improved laser beam profiles and distortion correction, and for electro-optic effects for controlling light by electric fields from electronics. A third-order material can be used to control light by light for intrinsic limiters for laser-hardened optics and for all-optical computing concepts.

The material properties for NLO materials are extremely demanding. The desirable properties include very large nonlinear optical responses, low power thresholds, fast switching speeds, high optical damage thresholds, low optical loss, thermal stability, temporal stability, and processability into optical quality films, fibers, and circuit components. We consider second-order materials, both inorganic and organic, and third-order organic materials. We note in passing that new phenomena are being discovered or realized in this area, so some of the boundaries are not even known. For example, it was demonstrated about three years ago that considerably larger effective third-order responses can be created through cascading, a phenomenon based on utilizing second-order material to introduce large nonlinear phase shifts obtained from phase-mismatched second-harmonic generation. For another example, only five years ago two-photon upconversion driven lasing was considered an impossibility. It has now been demonstrated by two independent laboratories. The field is obviously quite fertile.

Second-Order Materials. Second-order materials are needed to improve the performance and character of laser sources. These sources are basic to an incredible breadth of applications including IR countermeasures, remote sensing of chemicals, wind shear detection, medical diagnosis and treatment, materials processing, scientific instruments, optical communications, low-light imaging, atmospheric aberration compensation for astronomy and satellite tracking, scene projectors for testing and entertainment, optical signal processing, data storage, underwater communications and imaging, and remote identification of biological materials. Several materials are needed to optimize performance in each spectral band, and considerable success has already been realized in this regard. Emphasis should be given to developing improved crystal growth and processing techniques which are applicable to many material compounds.

Second-order materials are needed for electro-optic devices for applications including optical interconnects (i.e., data links), communications (requiring switches, modulators, and directional couplers), multichip modules, phase shifters for phased-array radar, and new sensors such as electric-field sensors. Lithium niobate ($LiNbO_3$) is currently used but is severely limited in a number of respects. Device fabrication cost is high, the electro-optic coefficient is low, leading to centimeter-size devices, the material is not integratable with electronic substrates, and device operating voltages drift with time.

Other inorganic ferro-electric materials such as barium titanate and lithium tantalate appear promising. Barium titanate shows particular promise, having a threefold improvement in figure-of-merit n^3r over $LiNbO_3$ and having recently been deposited with extremely high optical quality as single-crystal thin films on silicon substrates. An additional material system, semiconductor multiple-quantum-well structures, has already been proven viable in S-SEED devices, although performance is limited in certain regards. Crystalline organics, a third system, offer by far the highest nonlinearities known, and processing techniques appear feasible for integrating these films with semiconductor substrates. The final group, electro-optic polymers, appear inherently inexpensive with regard to processing and deposition, fast due a small dielectric constant, and integratable with electronic substrates.

These material systems appear promising, but each is limited in some way. Therefore, these systems should be pursued in parallel programs, eventually choosing a winner for continued development. Special emphasis should initially be given to electro-optic polymers due to their promising properties. Other areas worth pursuing include resonant two-photon absorbing materials. Two-photon absorbing materials hold great promise for the distant horizon for NLO applications. Unlike single-crystalline materials, two-photon absorbing materials require neither phase matching nor electric field poling. These characteristics would simplify manufacturing processes and eliminate second-order temporal stability problems. Very little is known for structure-property relationships for two-photon absorption, so this horizon is broad indeed.

Third-Order Materials. Third-order materials offer the possibility of revolutionizing the device architectures and capabilities of photonic and opto-electronic components. With third-order materials, completely optical analogs to electronic components are possible, such as all-optical transistors. The ultrafast response times of third-order materials make switches based on four-wave mixing enticing. The pressing need is for third-order materials with nonlinear optical responses (lower thresholds) increased by orders of magnitude. For logic units, nonresonance NLO effects are important. If these materials were resonance-driven, they would absorb too much energy, causing thermal expansion and degradation. Not enough discrimination between resonance-enhanced and nonresonance responses has been given in the third-order NLO materials field. Resonant materials are useful for optical limiting and sensor protection. With third-order materials, the response can be completely passive (i.e., dependent only upon the material and not any external fields). The Air Force should continue and possibly lead efforts to discover and develop new third-order materials. This is a clear technological driver for future components, and industrial efforts have decreased recently due to short-term priorities.

9.3 Summary

Long term vision is needed, and the Air Force should play a leading role in developing molecular and polymeric materials for electronic and photonic applications. There is serious discussion of molecular electronics — designing and building electronic and photonic functions into molecular and nanoscale components. While this seems almost science fiction, it may be feasible. The problems and opportunities outlined above for NLO and electronic materials are necessary stepping stones to the dream of molecular electronics. Additional steps worth pursuing include polymer-based photovoltaics and polymer electrode materials. Polymer photovoltaics will be significantly less dense than their inorganic counterparts. Spin coating manufacturing could make such devices very expensive. There is little or no work in this field. Much effort is directed toward polymer electrolytes for batteries, but little or no effort is focused on polymer electrodes. Conductive polymers have been demonstrated as polymer electrodes; concept demonstrations have been successful. In spite of initial and now abated excitement, it is astounding that there are no efforts to optimize chemical structure for these purposes. The Air Force stands to greatly benefit from such work. Multilayer, easy-to-form batteries would offer many design advantages for Air Force systems.